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Computerized Design Analysis of Machine Tool Hydraulic System Dynamics

Abstract

The design and analysis of most engineered systems involves many diverse technical disciplines. In the case of hydraulic systems, which are discussed in this paper, the actual input is some kind of prime mover such as an internal combustion engine or an electrical motor. The speed and torque of the prime mover is converted to the hydraulic power parameters at the pump, the directional control of the hydraulic power is provided by a valve, while the output can be the force and velocity of a reciprocating cylinder which may actually connect to the load through linkages and gears. The input to the valves can be electronic, hydraulic, or maybe manual. In addition, the output of the hydraulic system may be used in a feedback circuit which will normally encompass instrumentation, logic elements, and controllers. It is imperative that the design engineer be able in perform some kind of analysis to insure the proper function of diverse systems such as hydraulic systems. Such an analysis can be performed in the laboratory through the use of prototype systems, or it can be performed through computerized simulation. In order to evaluate the total performance, from input to output, of a hydraulic system analytically, a software program must be utilized which can integrate the interactions of the diverse components involved.

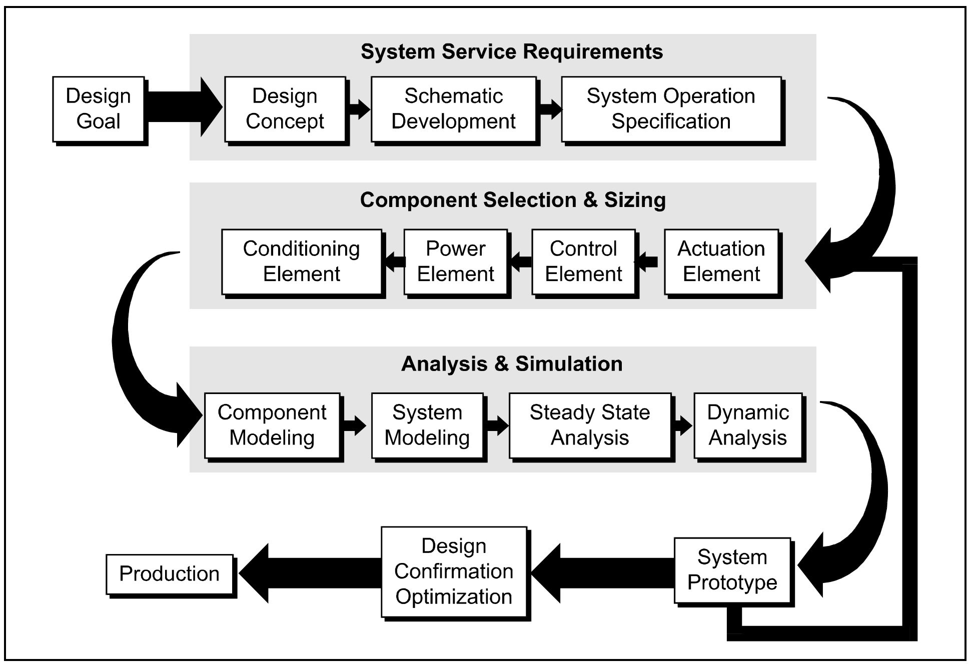
This paper will discuss the computerized design analysis of hydraulic systems using a computer program, called HyPneu, which is capable of integrating hydraulic, pneumatic, electronic, and mechanical components thus permitting the design analysis of complete hydraulic systems. The aspects involved in computerized design analysis will be discussed, followed by the illustration of the concepts through the use of example systems. These example systems will be simulated and the output information will be presented.

Introduction

Hydraulic systems can generally be broken down into two types of systems based upon the primary application. For example, on an earthmoving machine, the primary objective of the hydraulic system is to transmit power efficiently to the various circuits of the machine in an orderly fashion. On the other hand, a machine tool application is primarily concerned with speed, accuracy, and stability of the hydraulic systems. While every system is probably some compromise between these applications, due to space and time limitations, this paper will concentrate upon the machine tool type of application.

Once the design goals are established for a given hydraulic system, the actual design process can be initiated. The generalized hydraulic system design and analysis process is illustrated in Fig. 1[1]. From the design goals, the design concept to be integrated into the hydraulic system must be established and a system schematic must be developed along with the operational specifications for the system. Once these tasks are completed the designer will enter into the component sizing and selection process. In the past when the sizing and selection phase was completed, the components would be purchased and a prototype system constructed. The system performance was not simulated and the success of a particular system was mainly a result of the experience of the designer and luck. The actual performance characteristics were evaluated through laboratory and field tests using the system prototype. Optimization was a function of a process which was normally called “cut and try”.

Figure 1
Hydraulic System
Design & Analysis Process



The engineering world has long known that the analysis and simulation phase of hydraulic system development was very important in producing a successful hydraulic system in minimum time and cost. However, in the past, in order to effectively pursue the analysis, the engineer was required to be intimately familiar with hydraulic components and systems, and in addition be a mathematical genius and a computer expert. As a result, computer based analysis of hydraulic systems has been slow in evolving and being applied to design evaluation. Moreover, hydraulic systems usually involve the interaction of diverse technical disciplines which has made the implementation of system analysis on a Personal Computer (where it is available to most engineers) very challenging.

The breakthrough in the development of hydraulic system design analysis software came with the recognition that the behavior of real engineering systems is controlled by the flow, storage, and interchange of various forms of energy[2,3,4]. From this standpoint, system dynamics can be explored by describing mathematically all of the energetic actions and interactions in a given system. Depending upon the manner in which the various system elements handle the power flow and energy transfer, system elements can be classified as energy storage or dissipation elements. Furthermore, by realizing that all energy storage elements can be described by virtue of their A-type or by T-type variables, and the dissipation elements by virtue of their D-type variables, leads to the development of an analysis concept which is truly unified and can be applied with equal success to any engineering system. The A-type variables act ***across*** the elements such as velocity, pressure, and voltage. The T-type variables are for the energy which passes ***through*** such elements as force, current, flow rate, etc. The D-type variables are represented by such parameters as friction, resistance, orifice , etc.

A hydraulic system is composed of interacting elements and components. Therefore, once the element and component models are developed, the system model becomes a mathematical description of the way these elements and components interact. Two critical conditions must be satisfied when elements and components are connected together. These two conditions are compatibility and continuity. The compatibility requirement is applied to the ***across*** variables while the continuity conditions is used for the ***through*** variables. This signifies the conservation of mass and energy.

The remainder of this paper will provide a more thorough discussion of the approach taken to develop machine tool hydraulic component and system models. While the scope of this paper does not permit an in-depth treatment of the subject of modeling and simulation, the discussions will allow the reader to gain an appreciation of the methodology. The results of the analysis technique will be shown by example systems. The models and simulation data will be presented and discussed for each of the example systems.

Technical Background

With the development of very fast personal computers with large memory capacity, it became possible (even mandatory) to develop software which was capable of analyzing large hydraulic systems. These personal computers equipped with such software could sit on an engineers desk and provide an extremely important asset. In addition, the lack of adequate software slowed the design process and increased the cost of development for machine tool hydraulic systems. Any software package which would be the most useful to the designer of hydraulic systems must successfully handle such components as hydraulic, pneumatic, thermal, electronic, and mechanical. The philosophy of the HyPneu software is that a large number of so called generic components would be stored in a component library for use in any number of hydraulic systems. Special components which are manufactured for unique applications can be modeled and put into the component library for any engineer within the company to use. For example, a design engineer may be in the process of developing a very special valve. In order to evaluate the performance of the valve at any stage in the creative development process, it is necessary to perform either laboratory tests or obtain simulation results. Obviously computer analysis is much less expensive and time consuming provided that a model is be written. Once the special model for the valve is completed, enough generic components must be available to make up an entire hydraulic system. This is where the generic component library comes into play.

The foundation of the analysis approach used in this paper is ***visual modeling*** which relies upon the fact that all components are composed of several basic elements (e.g., mass, damper, spring, friction, orifices, etc.). The component library in the HyPneu program contains all of the basic elements of design in the form of icons, models, and data sheets. The user simply joins the correct icons together to form a complete component or system. Visual modeling requires a minimum amount of information and detailed knowledge concerning the laws of physics or the technology of modeling and simulation. As an example of this method, consider the typical two-stage nozzle flapper flow control servo valve shown in Fig. 2. Each element in this valve can be modeled by one or more of the basic design elements. Such a circuit is shown in Fig. 3. Notice that the torque gain, the armature dynamic, and the position feedback signal from the main spool are included in the modeling of the pilot stage. The mass and damping of the main spool are there, along with the metering orifices provided by the spool. Note that every element can be quantified using actual design dimensions and data to express the component function.

Figure 2
Two-stage Electrohydraulic Servovalve with Force Feedback

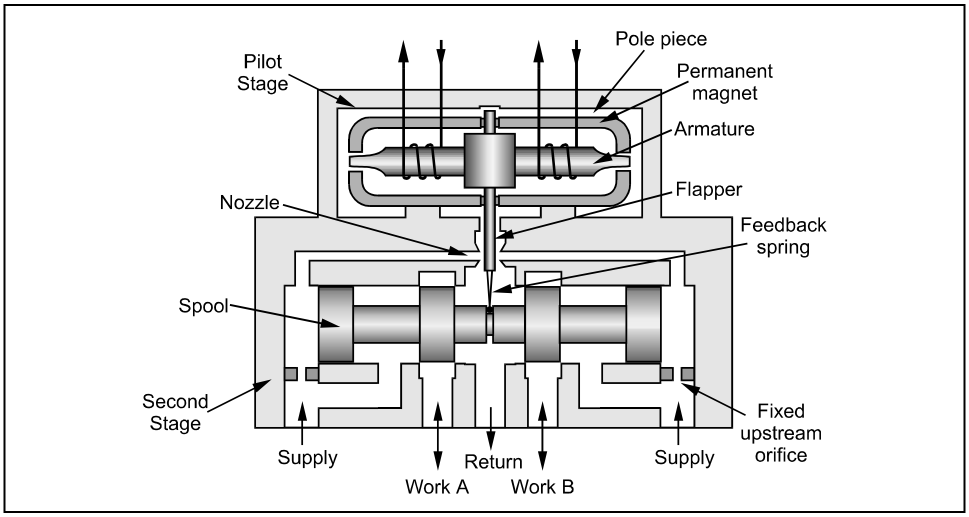
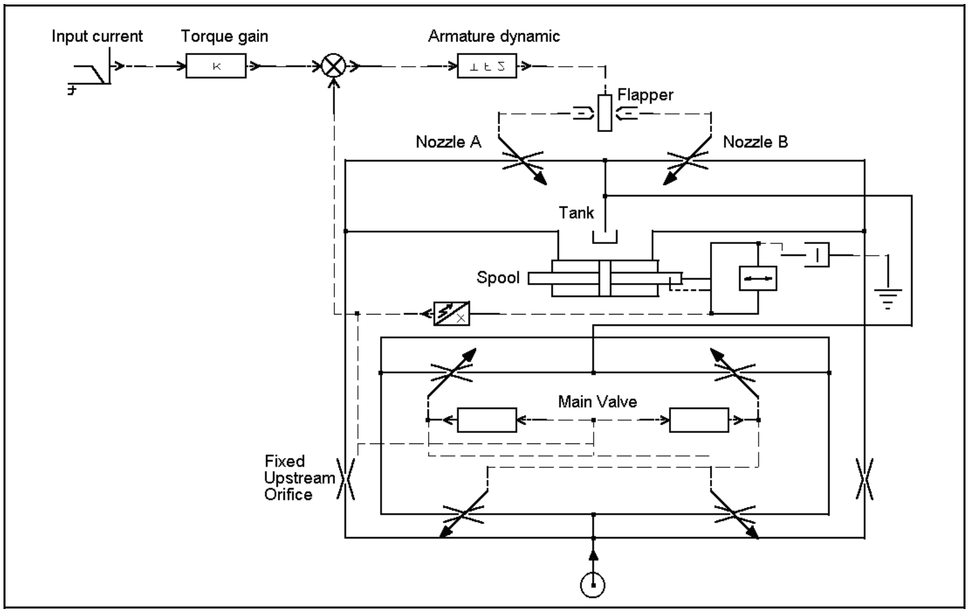


Figure 3
Nozzle-Flapper Servo Flow Control Valve



The method used in this paper permits a maximum degree of flexibility from an engineering staff. For example, one or two people can be assigned the task of developing the special component models which will arise in most creative design efforts. However, once this modeling effort is completed and verified, any engineer in the design group can use the model in system simulation.

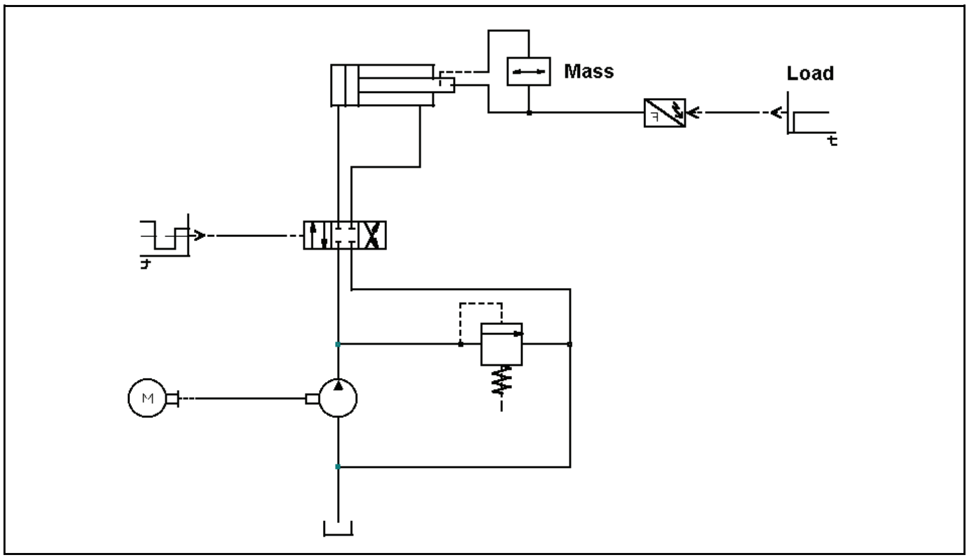
Case Studies

The versatility and simplicity of the analytical technique offered by the HyPneu program are the result of the visual modeling concepts and the unifying approach to the diverse disciplines involved in machine tool hydraulic components and systems. It is not possible to provide a complete description of the details of the technique, however, the following examples studies will illustrate a few of the industrial applications which have been addressed. Obviously, these examples have been simplified from the true real life applications. If such simplification was not employed the paper would exceed the space allowed.

Example #1—Simple Cylinder Control System

This case study involves the analysis of a simple cylinder system which includes a pump, a directional control valve, and a reciprocating cylinder as the basic components, as shown in Fig. 4. Such circuits are used in almost all hydraulic systems whether they are on machine tools or earthmoving machinery. The purpose of using this example is to illustrate a system problem and show the manner in which design analysis can be used to provide a solution. The main problem in this type of system, once the sizing and selection process is completed, is the dynamic characteristics. Notice that the circuit uses a closed center directional control valve. In addition, there are no components between the valve and the cylinder. Therefore, when the valve is energized to drive the cylinder (let's say) in the extend direction, the load will be accelerated as rapidly as possible to the maximum speed that the flow and pressure conditions will permit. Then if the closed center directional control valve is recentered, the cylinder rod and associated load will attempt to continue this motion. Very high pressure can be built up on the rod side of the cylinder in order to stop the motion. The fluid will be compressed by this high pressure, and will force the cylinder in the other direction. However, there is no place for the fluid on the head side of the cylinder to go with the valve in the centered position. This is the typical water hammer phenomenon which occurs all too often in fluid power systems.

Figure 4
Simple Cylinder Control System



The simulation results for the system is shown in Fig. 5. Notice that the pressure oscillations are continuous because there is no way for this phenomenon to be damped out. The damping normally comes from the leakage passed the cylinder piston. However, to be certain that there will be no water hammer and to insure that excessive and sharp external loads will not burst a connector or buckle the cylinder rod, it is common practice to use circuit or crossover relief valves along with meter out check valves such as shown in Fig. 6. The simulation results from the circuit shown in Fig. 6 is shown in Fig. 7. Notice in these simulation results that the water hammer is damped and the system becomes stable in a very short period of time.

Figure 5
Simulation Results of Cylinder Control System

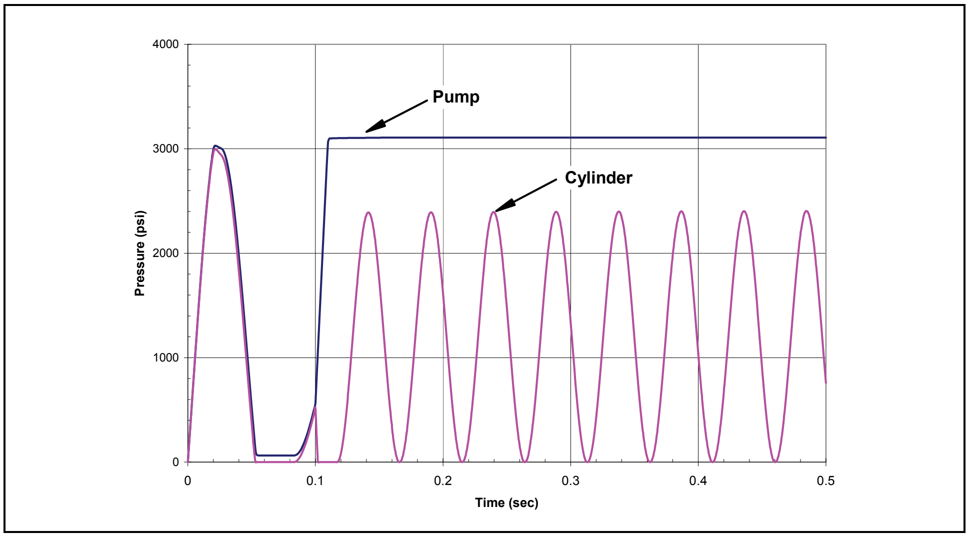


Figure 6
Modified Cylinder Control System

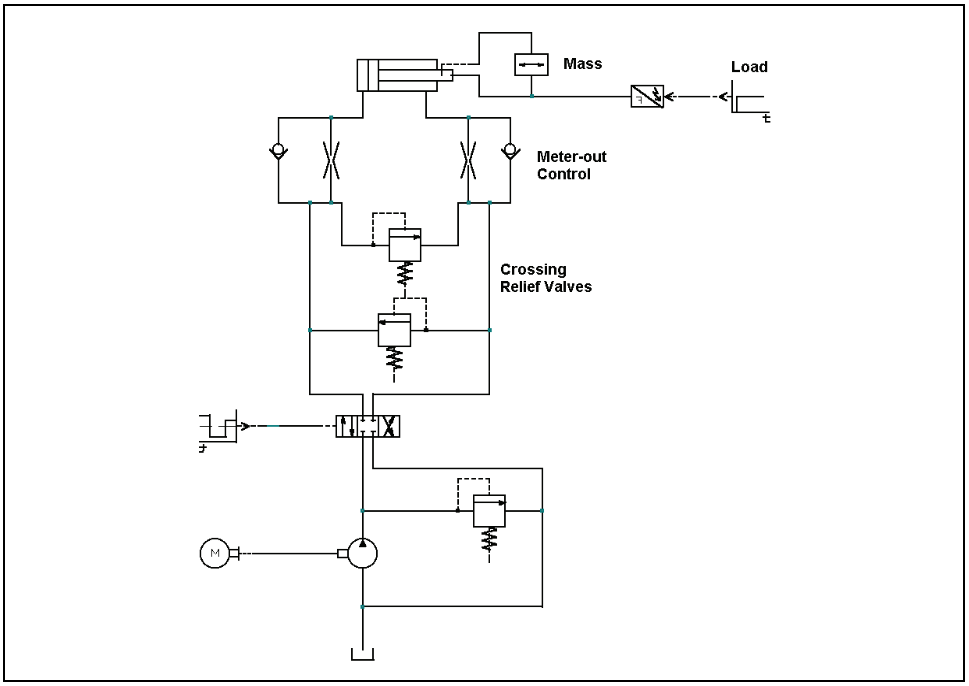
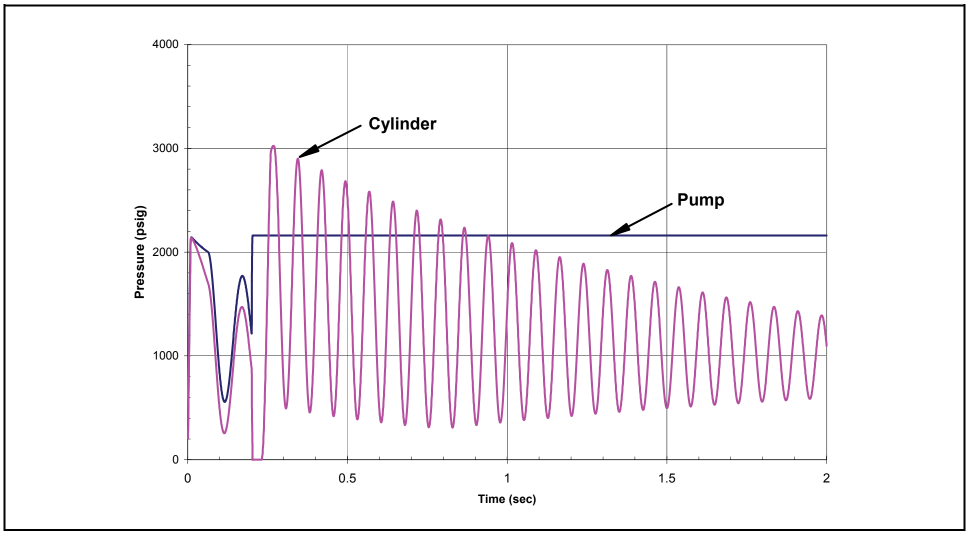


Figure 7
Simulation Results from Modified Cylinder Control System



Example #2—Robot System

The robot is a ubiquitous machine in many manufacturing facilities today. The example system shown schematically in Fig. 8 is a simple robotic system consisting of one pivot actuator circuit and two reciprocating actuator circuits. It should be noticed that even though this robot is not intended to handle heavy loads, it has been equipped with counterbalance valves and crossover check valves to prevent the sudden loss of a load. The system basically consists of a single pressure compensated pump supplying fluid to three directional control valves. Each circuit has a position signal which uses the directional control valves to move the function to the desired location. In a real application the position signal would come from a program which determines the required location relative to the current location of the function. The simulation results using only the pivot actuator from the robotic system shown in Fig. 8 are given in Fig. 9. The parameters plotted are the pressure to move the pivot actuator and the angular displacement of the actuator.

As can be seen from Fig. 9 the pivot actuator is unstable when it reaches the required location. This occurs because the system is very stiff, employing steel lines and very little volume of fluid. The valve has critical lap metering at the null position. The crossover checks require 2000 psi to open. Therefore, when the desired location was reached there was some overshoot and the control system reversed itself to correct the overshoot. As mentioned, it requires 2000 psi to open the crossover check valves. With very little load on the actuator, it moves very quickly once the check valves open, and will overshoot in the other direction. This will continue first in one direction and then the other. The solution to this problem of stability can be solved by removing the crossover check valves. However, a problem of safety at large loads would exist. The safety issue can be resolved by using pilot checks in place of the crossover check and using the pump outlet pressure to actuate them. The modified robotic system is shown in Fig. 10 while the simulation results for the modified robotic system are given in Fig. 11 for the pivot pressure and angular motion.

Figure 8
Robotic System Schematic with Counterbalance Valves

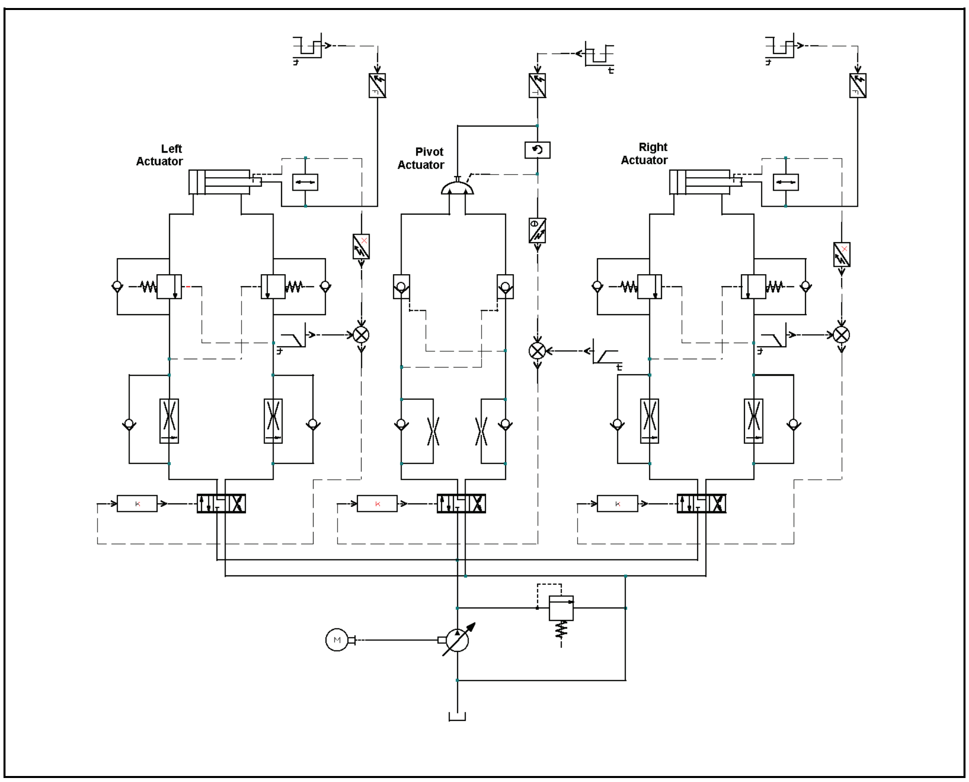


Figure 9
Simulation Results from Robotic System with Counterbalance Valves

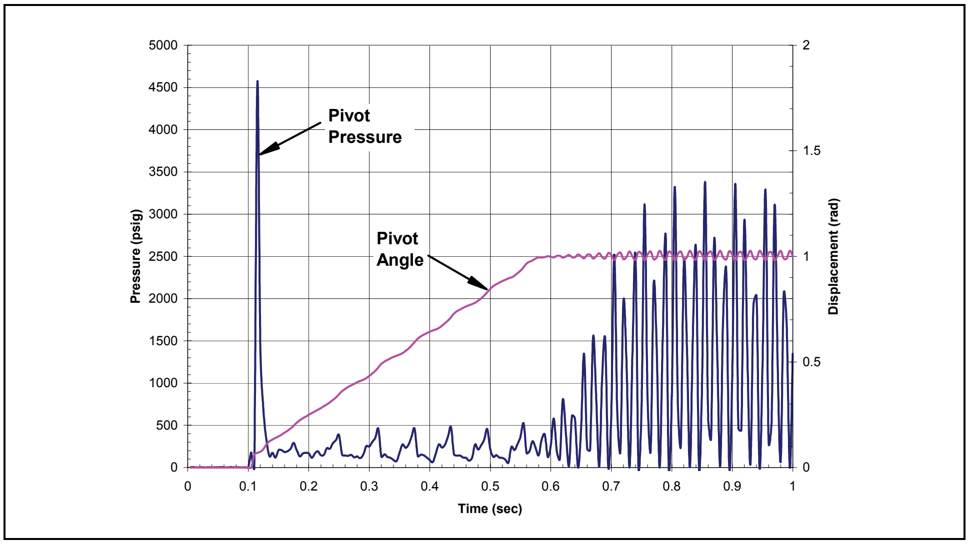


Figure 10
Modified Robotic System Schematic

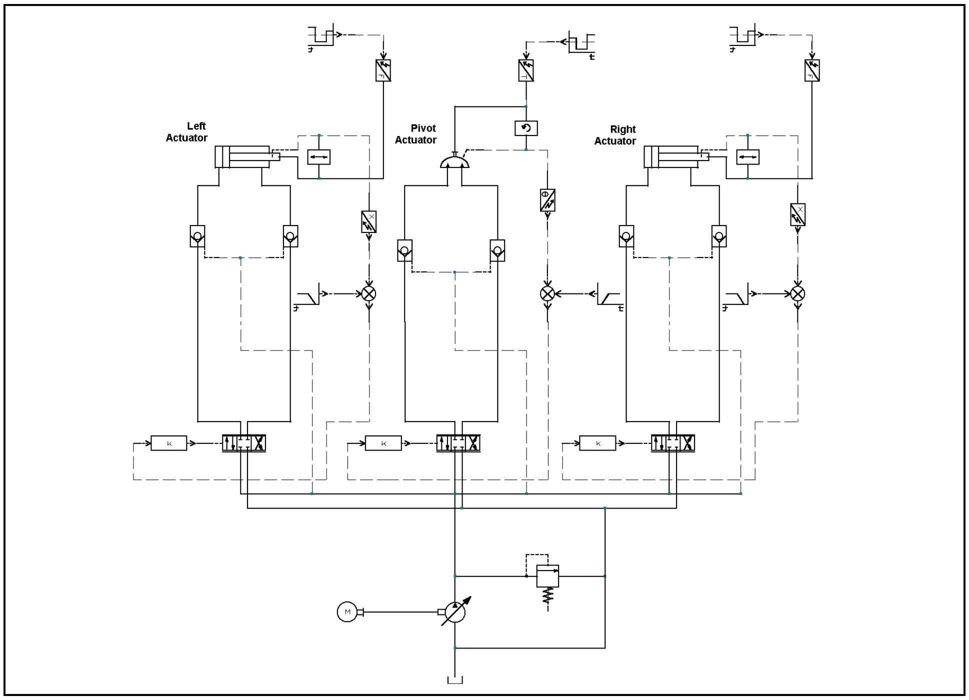
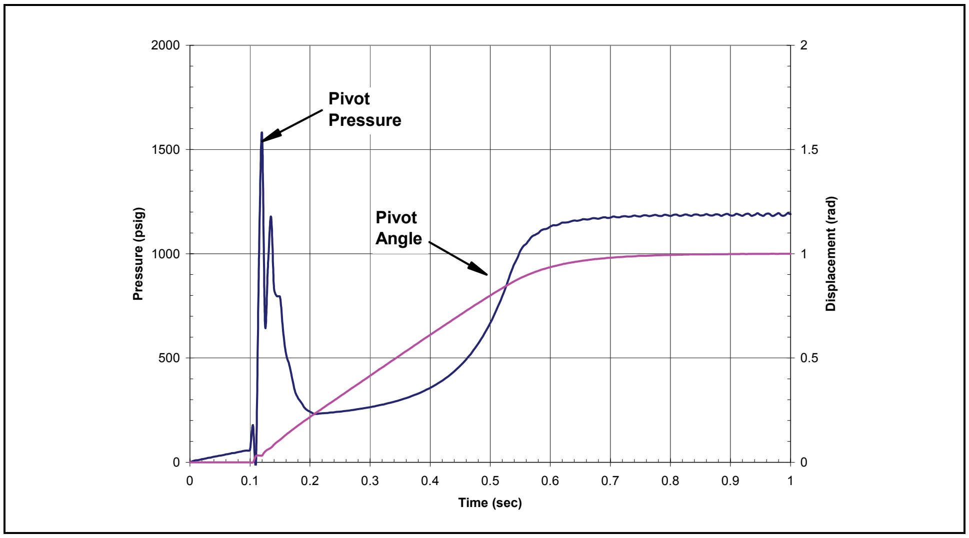


Figure 11
Simulation Results from Modified Robotic System



Example #3—Regenerative Machine Tool Hydraulic Circuit

In order to increase productivity it is common to use a hydraulic system called a regenerative system. This is a system where a reciprocating cylinder with a single rod is used to move a work piece into position. For most of its travel the positional accuracy of the work piece is not of concern. Therefore, the cylinder can be extended very rapidly until the required position is nearly reached. At this point the speed is reduced such that accuracy is enhanced. In recent years this has been usually accomplished with cartridge valves as shown in Fig. 12, while Fig. 13 shows a regenerative system using a spool type valve controlled by a PLC (Programmable Logic Controller) component. The simulation results of the regenerative system is shown in Fig. 14.

Figure 12
Regenerative Circuit with Cartridge Valves

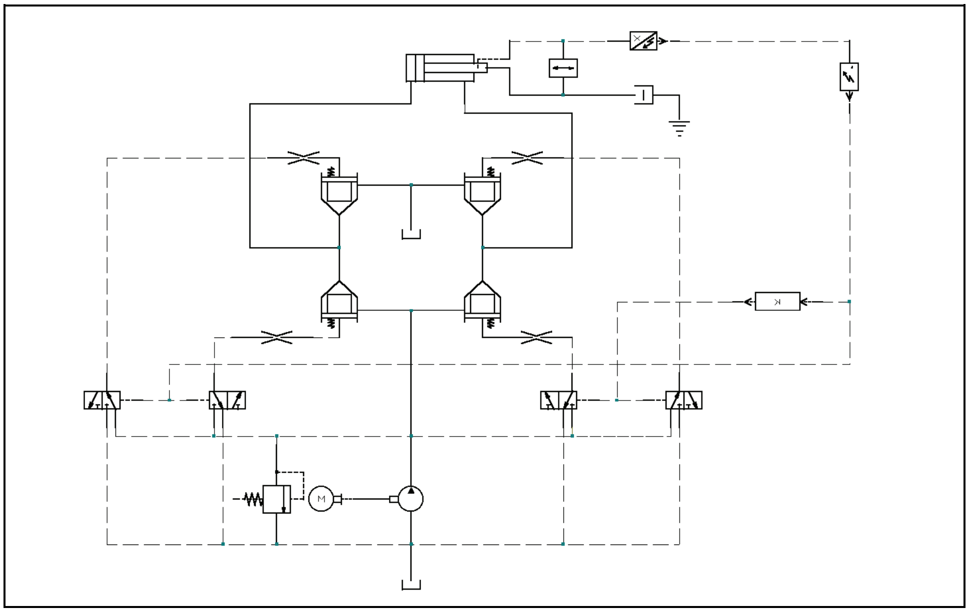


Figure 13
Regenerative Circuit with Spool Valve

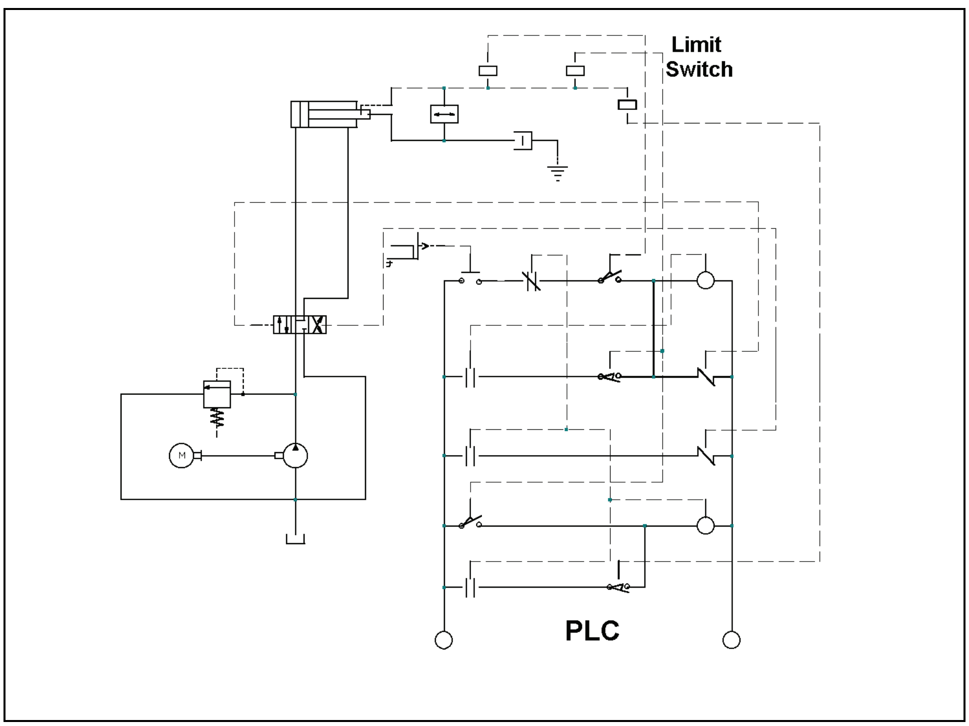
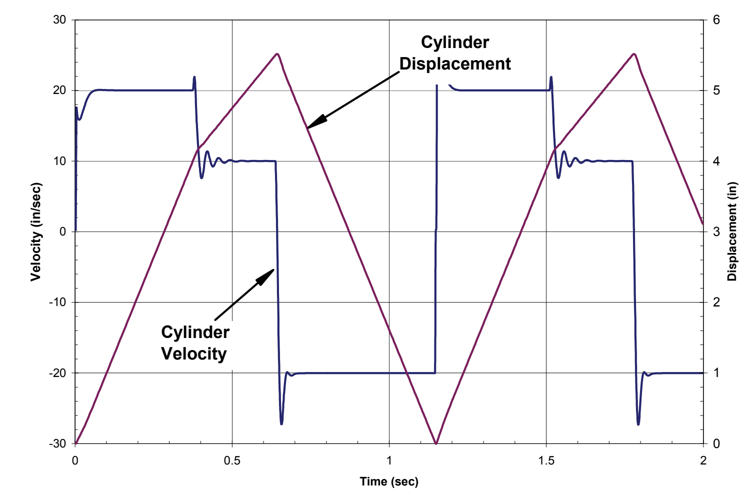


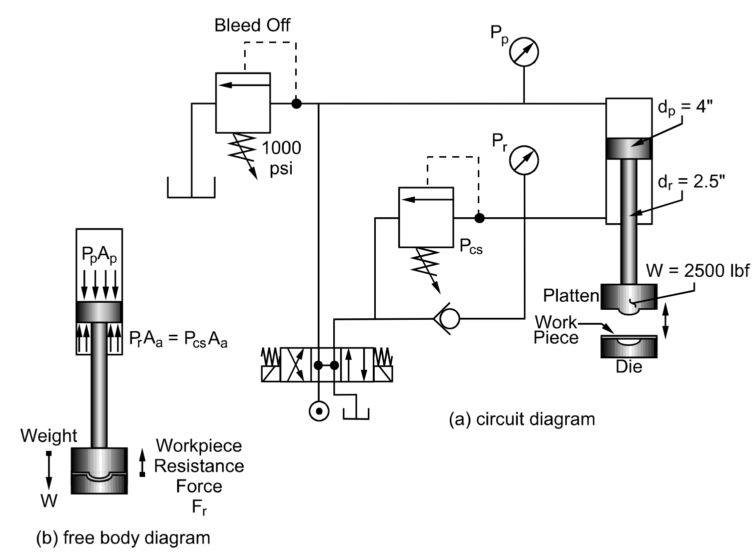
Figure 14
Simulation Results from Regenerative Circuit



Example #4—Hydraulic Press System with Direct Acting Counterbalance Valve.

One of the most widely used hydraulic systems in the machine tool area is the press system. The hydraulic press system is many times equipped with a direct acting counterbalance valve or an overcenter valve. In the example used here the direct acting counterbalance valve is incorporated. The hydraulic press system generally utilizes a large double acting cylinder with a large rod. There is a heavy platen attached to the rod which acts to extend the cylinder. Therefore, the natural tendency is for the platen to move under its weight. The direct acting counterbalance valve is used to prevent such movement and provide back pressure to enhance controlability. A schematic of the hydraulic press system is shown in Fig. 15 while the HyPneu schematic is given in Fig. 16. For the purpose of simulation, the platen is suspended initially. The fluid is introduced into the cap end of the cylinder at 0.25 seconds. The cylinder will begin to move when the cap end pressure reaches 237 psi. The platen reaches the die at about 1.2 seconds. When the platen reaches the die the cap end pressure increases rapidly to produce the pressing force. The HyPneu simulation results are given in Fig. 17.

Figure 15
Hydraulic Press System with Direct Acting Counterbalance Valve.



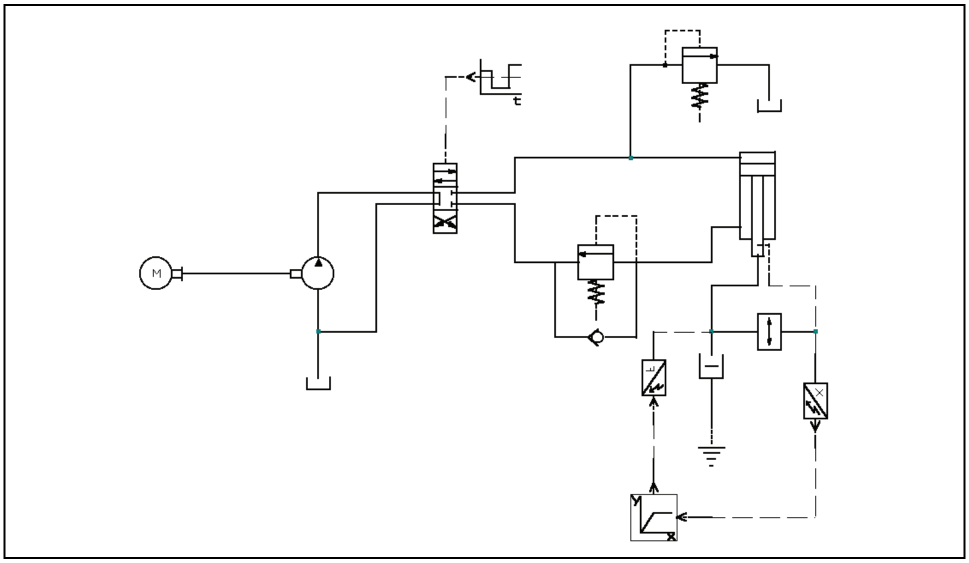


Figure 16
HyPneu Circuit for Press System with Direct Acting Counterbalance Valve.

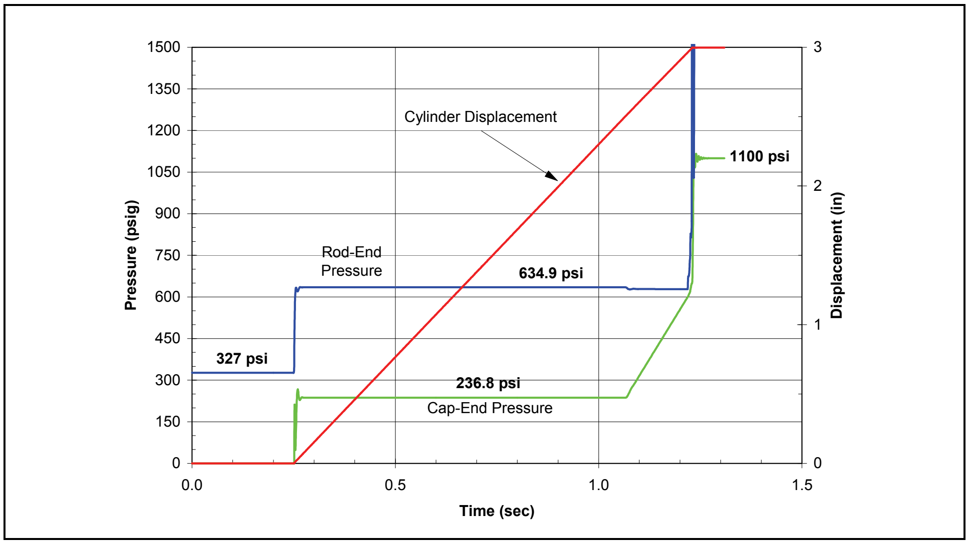
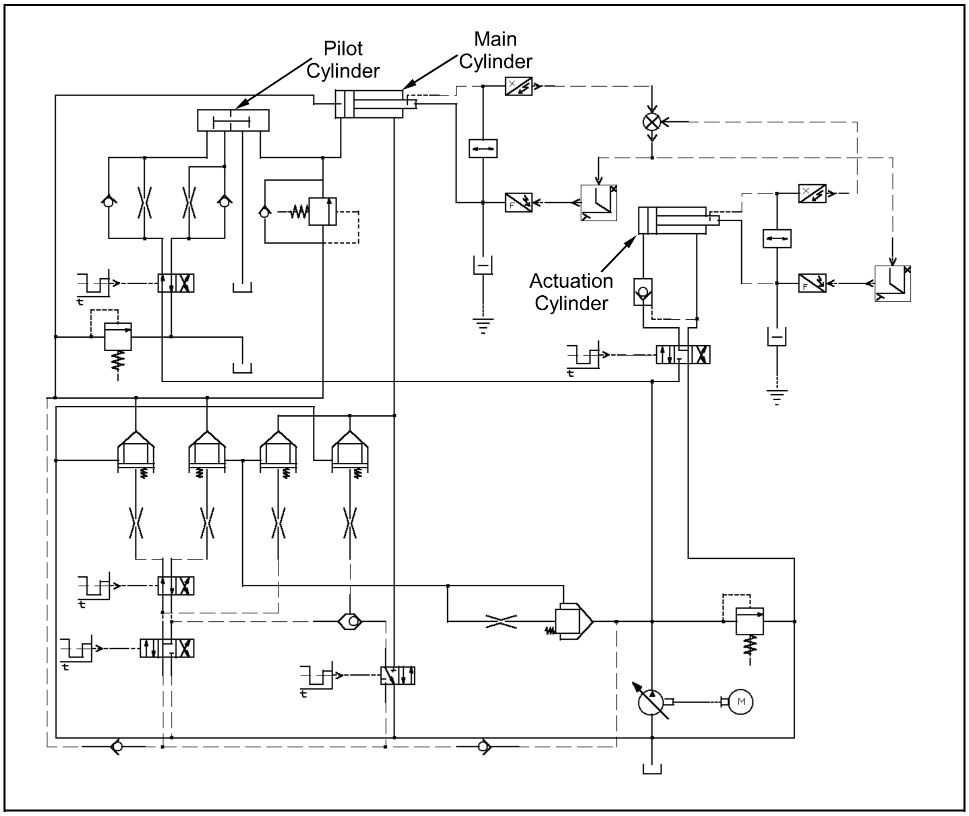


Figure 17
HyPneu Simulation Results for Press System with Direct Acting Counterbalance Valve.

Example #5—Plastic Injection Molding Machine.

The plastic injection molding machine is a popular piece of equipment in light industry applications. To achieve consistency in plastic product quality, a number of variables must be controlled—shape, dimension, and material properties. The design of the product determines whether the magnitude of the variations in pressure, temperature and time is acceptable. A design with wall thickness variations, a variety of openings, and a complex shape demands a much closer limit of the variables. In practice, the hydraulic system provides the horsepower for a plastic injection molding machine. Because of the versatile functions available and the easy maintenance, cartridge valves have gained great popularity in accomplishing the control functions of the plastic injection process. Fig. 18 illustrates a hydraulic system that was implemented on a plastic injection molding machine.

Figure 18
Hydraulic System for controlling Plastic Injection Molding Process.



The injection molding process consists of six separate steps as given below:

1. Close mold
2. Increase mold pressure and hold the pressure
3. Relieve mold pressure
4. First stage open mold
5. Second stage open mold with differential pressure
6. Process completion

This process is achieved by a mold clamping unit, as shown in Fig. 19, together with cartridge valves and their supporting logic hardware and software. The process is controlled by five signals denoted as S1, S2, S3, S4, and S5. The signals and their cycle times are shown in Fig. 20(c). Signals S2, S3, and S4 are connected to control valves that influence the pilot pressure of the cartridge valves while S1 and S5 are signals to the pilot cylinder and the actuation cylinder. Fig 20(a) shows the HyPneu simulation results compared with actual process testing data and Fig. 20(b) reveals the simulation results of the actuation cylinder velocity.

Figure 19
A molding Clamping Unit.

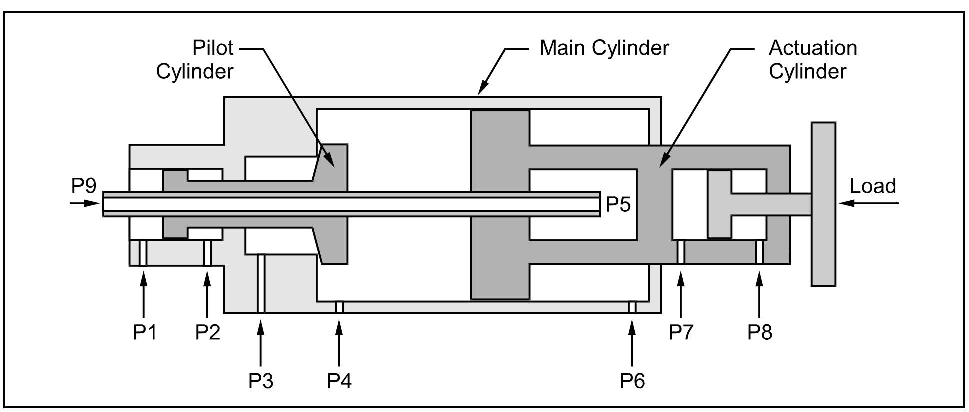
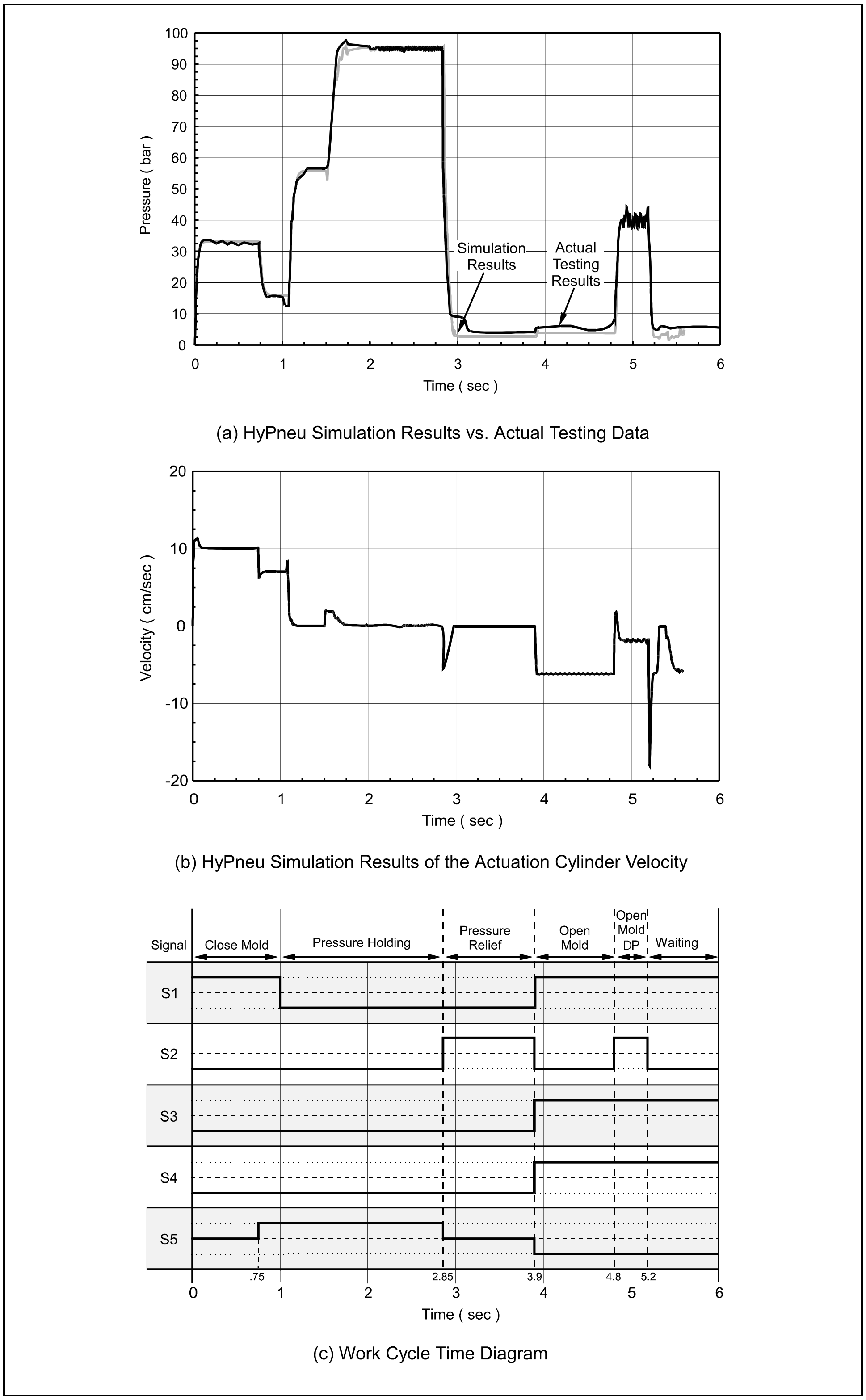


Figure 20
Plastic injection Process Pressure and Velocity Profiles



Summary and Conclusions

The purpose of this paper was to discuss the development of hydraulic systems for machine tool applications. The costs of a development program have spiraled to a level where only the companies who can develop products effectively and efficiently will survive to do business in the future. In the past, hydraulic system development has meant that the system would be created from experience and knowledge. From the schematic it was necessary to procure or manufacture the components and assemble the system before any laboratory test could be conducted to either confirm or deny the excellence of the design. If the system performs satisfactorily, and incurs minimum costs the first time it is assembled, then there is nothing wrong with this design approach. However, all too often the system does not perform the way it was intended or it costs far too much. Then the design must be altered and reassembled in order to determine if the alterations have succeeded in producing the optimum system. Companies can no longer afford such costly and time consuming practices.

It has long been known that modeling and simulation could be used to analyze engineered systems prior to assembling a prototype system. However, the engineer that was assigned the task of modeling and simulating a hydraulic system had to be somewhat of a genius to accomplish the mission in a timely manner. He had to not only understand hydraulic component and system interactions but he had to be a mathematician, a physicist, and a computer programmer. Adequate computers were not at his disposal, nor did he have effective software. When the large, fast desktop personal computers came about adequate computers were finally available. In fact, now there are portables and laptop computers which are perfectly adequate to run efficient modeling and simulation software. Now there are computer programs available which can make the design and development of machine tool hydraulic systems cost effective.

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